Interhemispheric drift of radioactive debris and tropical circulation

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ABSTRACT

Following French nuclear tests on Mururoa Atoll in the south Pacific (test site, 21° S, 138° W) during the northern summers of 1966–68, a high level of surface-air radioactivity was measured at stations in both the hemispheres. In particular, the effect of the 1968 French test was detected in the northern hemisphere up to a latitude of about 50° N. Relevant data for a few stations are presented. Available meteorological data for 1968 are examined to determine the air currents by which radioactive debris from the tests carried out during this year drifted to the northern hemisphere. South Pacific data appear to rule out the possibility that the debris from the test site was transported to the equator and beyond exclusively by the lower-tropospheric trade wind circulation. On the basis of global tropospheric cirulation data presented it is suggested that the interhemispheric transport was effected by the trade wind circulation after the debris had been transported by the tropical westerlies to latitudes nearer the equator by lateral diffusion. Available data suggest that the lateral diffusion coefficient of the tropical westerlies of the southern hemisphere may be of the order of 10^6 m^2 sec^{-1} or more. In the west Indian Ocean the trade winds near the equator have strong meridional components, hence when the debris arrives by way of the tropical westerlies it is rapidly transported across the equator by the trade wind circulation. The study appears to support qualitatively earlier work in respect of transequatorial fluxes of air in the lower troposphere in the west Indian Ocean during the summer monsoon season and suggest generally that large transequatorial fluxes should occur in such regions where the intertropical convergence zone (ITCZ) lies well away from the equator in the opposite hemisphere. Meridional motion associated with ITCZ may transport the debris equatorward or poleward depending upon its location within a hemisphere.

In case of poleward transport, the debris may arrive at a latitude from where the westerlies can spread it to higher latitudes.

1. Introduction

The last two-and-a-half decades have witnessed a large number of nuclear tests in the atmosphere. Till 1966, these tests were mostly confined to the northern hemisphere and carried out at various latitudes ranging from the arctic to the equator. Numerous studies have been made of the atmospheric transport of radioactive debris from these tests and the general finding has been that zonal transport as well as lateral mixing is very rapid in high and middle latitudes but, coming to low latitudes, these processes slow down considerably. However, radioactive debris from quite a few of these tests drifted to the southern hemisphere (Staley, 1963; Woodward, 1966). Staley (1963) who noted the difference in the rate of interhemispheric drift between the 1961 Russian tests in Siberia and the arctic (test sites, 52° N, 78° E and 75° N, 55° E) and the 1962 American test on Christmas Island (test site, 2° N, 157° W) remarked that the rate of interhemispheric drift depends crucially upon where exactly within the hemisphere the debris is concentrated. Junge (1962) had indicated a possibility that interhemispheric drift through monsoon circulation might be very rapid. Between 1966 and 1968 the French exploded a series of nuclear bombs in the southern hemisphere (test site, 21° S, 138° W) details of which are given in Table 1. Following these tests, large increases in surface-air radioactivity were detected not only at southern hemispheric stations but also at stations in the northern hemisphere. Rangarajan et al. (1969*a*, *b*) have re-

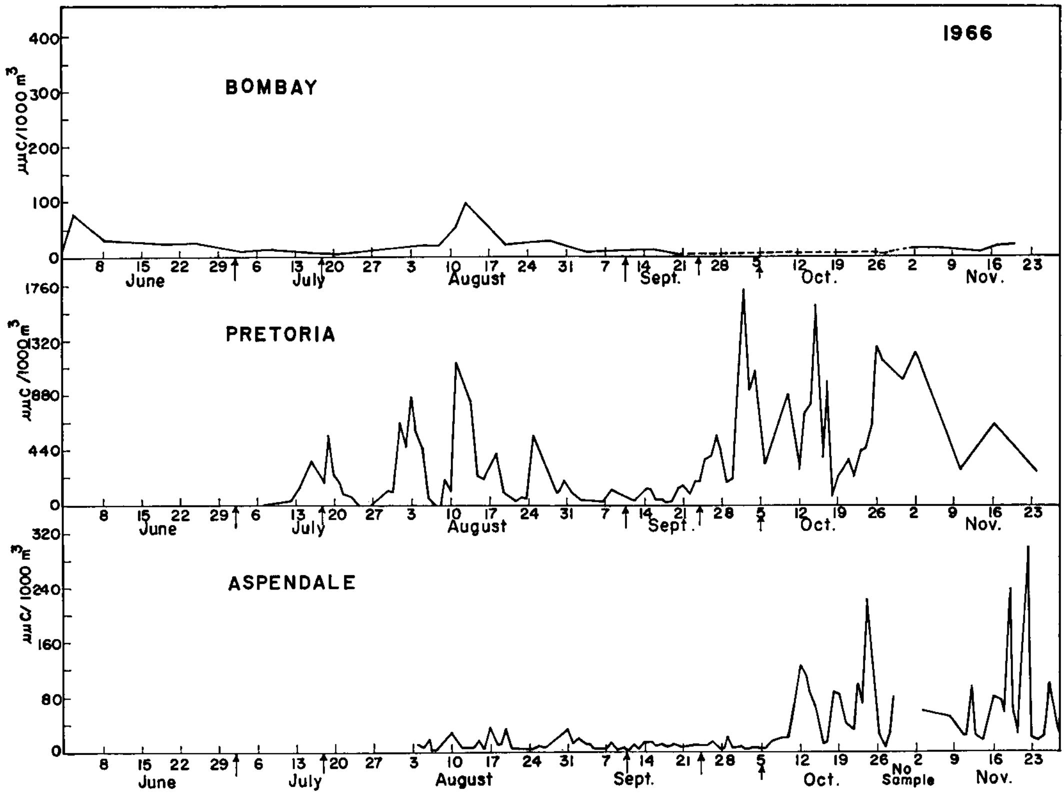

Fig. 1. Measured values of Zirconium-95 concentration in surface air at Bombay (19° N, 73° E), Pretoria (26° S, 28° E) and Aspendale (38° S, 145° E), June through November, 1966. Unit: pCi/1 000 m³. Vertical arrow-heads on baseline indicate test dates.

ported that the effect of the French tests was detected at a number of monitoring stations in India in all three years (1966–68). The effect of the 1968 French tests was detected at Hongkong (22° N, 115° E) during the week 19–26 August, at Gibraltar (35° N, 5° W) two weeks later, and in the UK by the end of September (Cambray et al., 1968) and at a number of stations in America, e.g. Fort worth (33° N) by early August and Argonne (42° N) and International Falls (48° N) later (Gustafson et al., 1968). Rangarajan et al. (1969*b*) have, however, pointed out that the 1968 French test debris was detected earlier and in significantly larger quantities in India than in other areas of the northern hemisphere.

The object of the present study is to examine with the aid of available meteorological data those aspects of tropical circulation which were responsible for the transport of the radioactive debris across the equator following the 1966–68 French tests. Possible mechanism for penetration of the 1968 test debris deep into the northern hemisphere is also examined. Meteorological data for the year 1968 are selected for detailed study.

2. Radioactivity data

Cambray et al. (1966, 1967, 1968) have given daily and weekly averages of the concentration of short-lived radio-nuclides in surface air, such as Ba-140 (half-life = 12.8 days), Zr-95 (half-life = 65 days) etc., at Pretoria (26° S, 28° E) and Aspendale (38° S, 145° E) in the southern hemisphere and Hongkong and Gibraltar in the northern hemisphere, and Rangarajan et al. (1969*a*) have given the corresponding values for Bombay (19° N, 73° E) and other Indian stations. From these and from magnitudes of such ratios as Ba-140/Zr-95 or Zr-95/Cs-137, they have estimated the times of travel

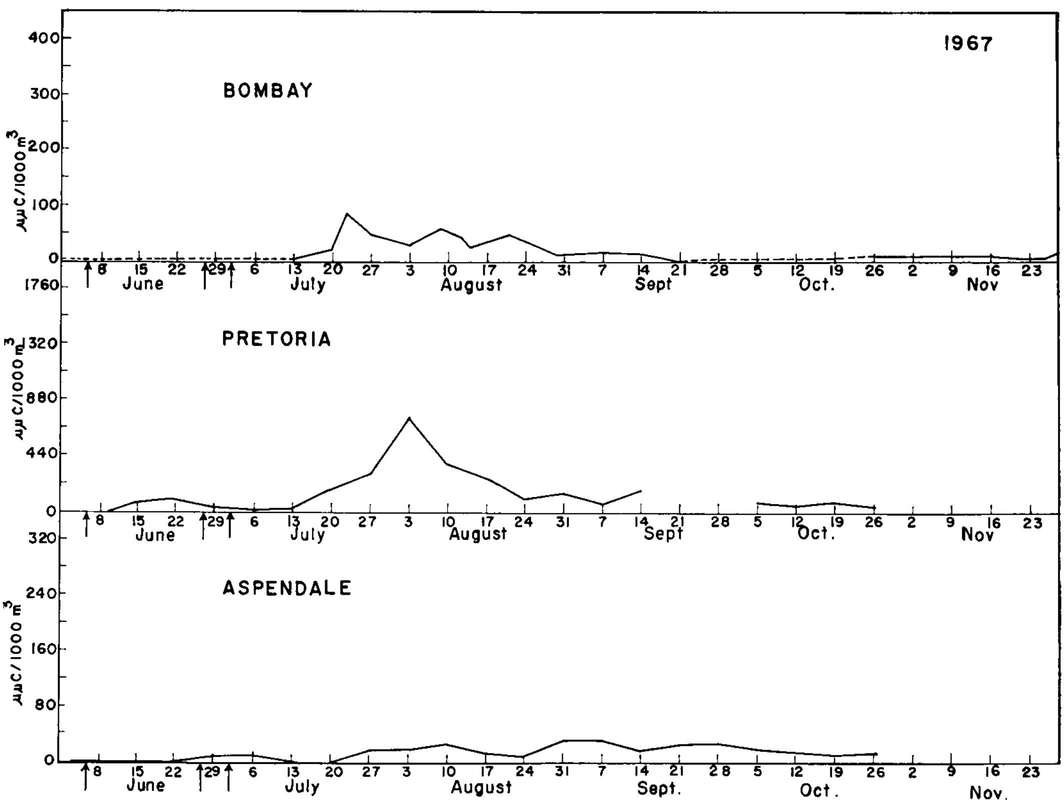

Fig. 2. As for Fig. 1, 1967.

of the debris to the monitoring stations. The details in respect of Bombay, Pretoria and Aspendale, adapted from their reports are included in Table I. Figs. 1 through 3 give the level of concentration of Zr-95 in surface air at these stations during June through November in the individual years. It may be noted that of the two series of tests carried out during 1966, the first during July is only feebly detected at Bombay whereas the second during Sept.–Oct. although of higher yield, is hardly detectable at the station. At the hemispheric stations Pretoria and Aspendale, however, both the test series were clearly detectable. The 1967 and 1968 tests were clearly detected at Bombay but the effect of the 1968 test was much more pronounced. The distinctive features of the effects of the French tests in regard to both hemispheric and interhemispheric transports are shown in Fig. 4 which gives the monthly concentration of gross gamma radiation at the HASL network stations along the 80° W meridian during period 1965 through 1968 (Volchok et al., 1969). The following features of Fig. 4 would seem to be noteworthy:

(*a*) The background radioactivity in both hemispheres was low during June through October, 1965, when there was no nuclear test.

(*b*) Two separate series of nuclear tests during 1966, one during July and the other during Sept.–Oct. are well testified by two periods of peak concentrations.

(*c*) The hill station, Chacaltaya (5 220 m) shows consistently higher values of radioactivity than neighbouring low-level stations. Data at Portillo (2 850 m) were available during 1966 only and appear to exhibit similar higher value.

(*d*) The maximum concentration appears to be confined to within a few degrees of the test latitude, apparently signifying that the mean transport of the debris cloud is predominantly zonal although there is considerable lateral dispersion of the debris material.

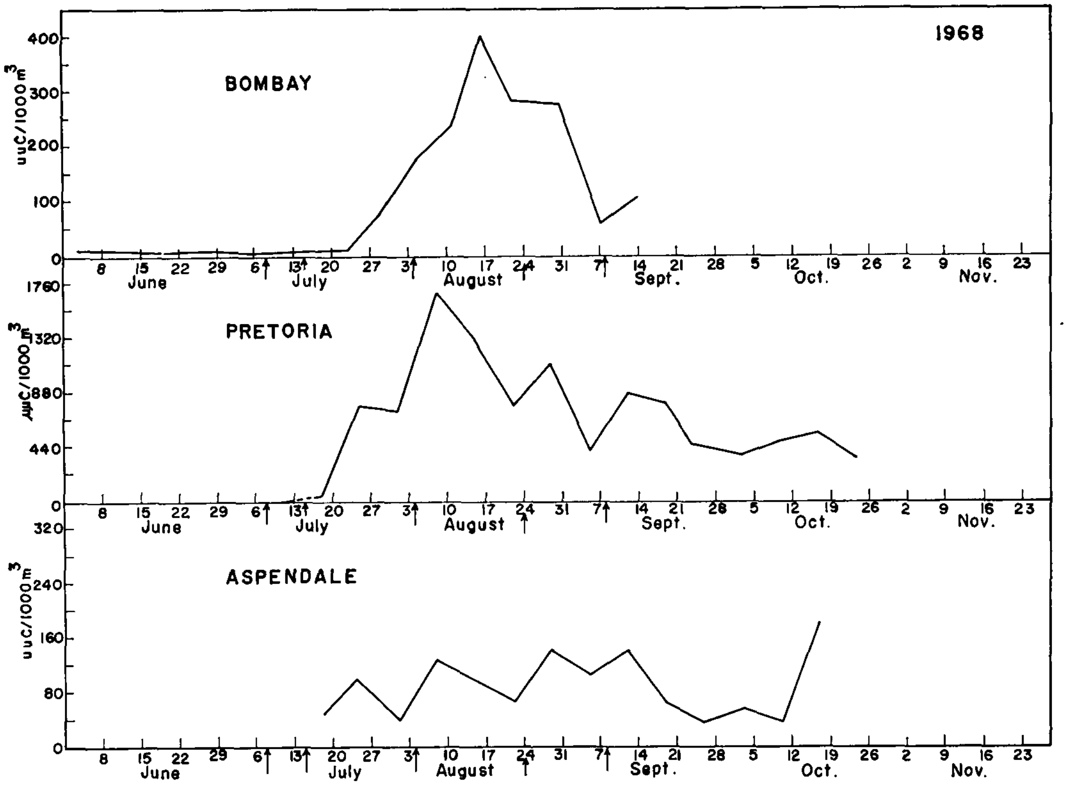

Fig. 3. As for Fig. 1, 1968.

(*e*) During 1966 and 1967, the radioactive debris extended only slightly north of the equator. During 1968, the penetration is much deeper.

The above features are also exhibited by values of monthly concentrations of short-lived radionuclides, Ce-141, Sr-89, and Zr-95, along the 80° W meridian. These values are not presented for lack of space.

3. Meteorological data and atmospheric circulation

Since the French tests were in the low- and medium-yield ranges (except the last two of the 1968 series which were in the megaton range), it is likely that bulk of the radioactive material which is contained in the mushroom cloud was confined to the middle and upper troposphere and drifted with the tropospheric winds (Kellogg et al., 1957). As mentioned earlier, meteorological data for 1968 only will be examined in the present paper for detailed study. Fig. 5 which is a mean meridional cross-section through the mid-Pacific (Mean meridian about 160° W) shows the vertical distribution of mean zonal components of prevailing winds during July, 1968. Similar meridional cross-sections for four other regions of the global tropics, viz. (*a*) 60°–80° W, (*b*) 15°–30° E, (*c*) 75°–90° E, and (*d*) 140° E are shown in Fig. 6. Briefly, each of these cross-sections brings out the major salient features of the tropical general circulation, viz two broad belts of westerlies, one in each hemisphere, separated by a broad belt of easterlies, but there are important regional differences. Fig. 5 and section (*a*) of Fig. 6 show that the belt of upper tropospheric westerlies of the southern hemisphere above about 250 mb level extend across the equator to about 10°–15° N. Sections (*b*), (*c*) and (*d*) of Fig. 6 show a belt of low level westerlies near the equator in place of the easterlies. Equatorial westerlies appear most prominently in the regional cross-section (*c*) through the Indian Ocean where they extend at surface

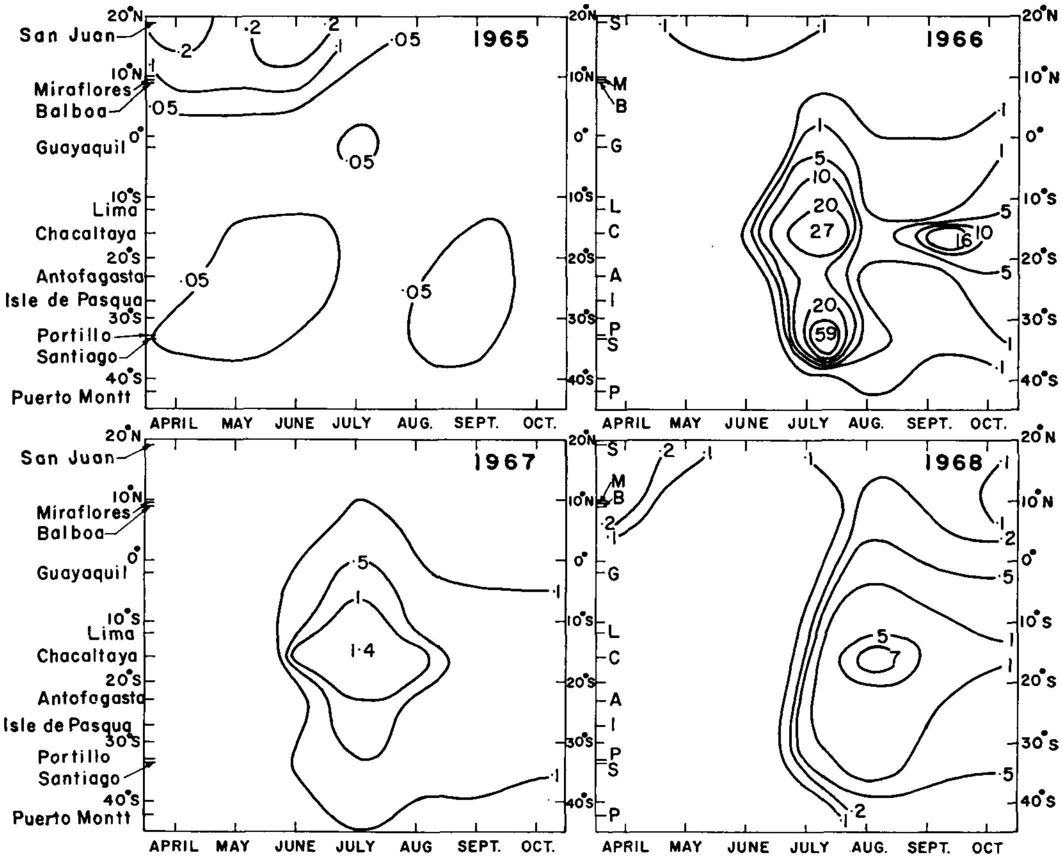

Fig. 4. Monthly values of Gross gamma concentration in surface air during April through October, 1965–68, along 80° W meridian. Unit: Thousand Photons/min/1 000 standard m³.

from near 25° N to about 5° S, their depth gradually increasing towards the south and attaining about 6 km a.s.l. near the equator. In the African and Australian regions, the equatorial westerlies are mostly confined below 700 mb level. Another major feature revealed by Figs. 5 and 6 is the small depth of the layer of the trade wind easterlies (~1.5 km a.s.l.) at the test site compared with the depth of the overlying westerlies which cover practically the whole troposphere and extend even beyond the 100 mb level. This difference in the depths of the two aircurrents forms an important consideration in the discussion of the transport of the debris from the test site. Fig. 7 presents the mean streamlines at 850 mb level during July 1968 over the Pacific and the Indian Ocean region. The distribution of the zonal and meridional components of the streamlines shown in Fig. 7 along the equator and four other latitudes (10° and 20°, N and S) are presented in Fig. 8. These show that the meridional components of the lower tropospheric trade wind circulation are the strongest near the equator in the west Indian Ocean. Strong meridional components of winds near surface in the west Indian Ocean may also be seen in a synoptic map at time 12Z on 12 July 1968, presented in Fig. 9.

4. Hemispheric transport and lateral diffusion

Meteorological data presented in the previous section leave little doubt that after formation at the test site, the bulk of the mushroom-shaped debris cloud which contains most of the radioactive material comes under the influence of the upper westerlies. Figs. 5 and 6

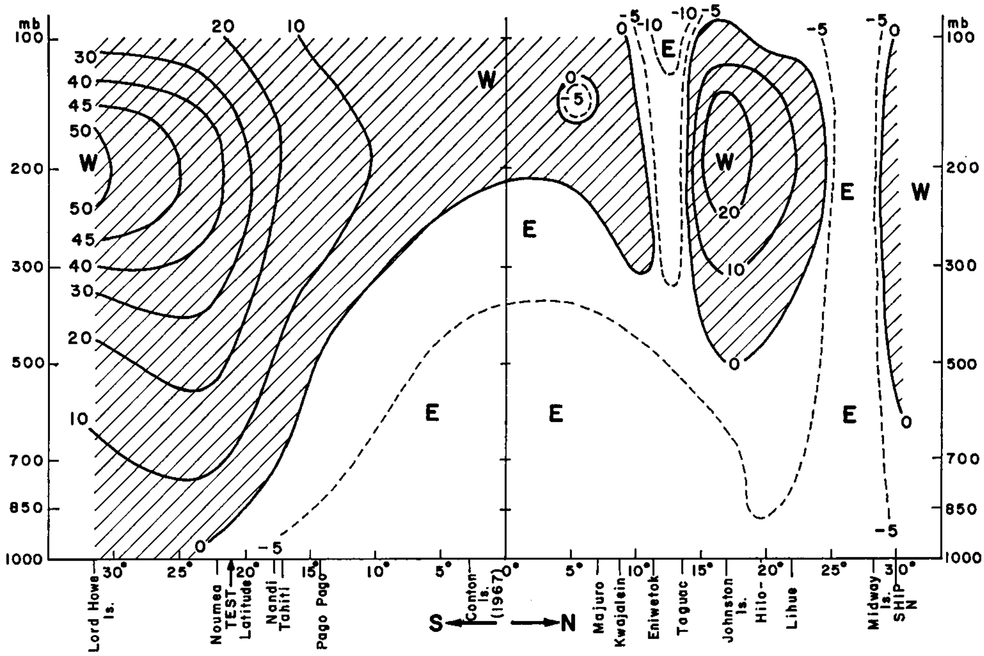

Fig. 5. Vertical distribution of mean zonal components of winds, surface to 100 mb level, between 30° N and 30° S, along meridian 160° W, (Pacific Ocean) during July, 1968. Shaded area = westerlies. Speed in m/sec negative for easterlies. Test site latitude is shown by a vertical arrow head on base line.

Table 1. *Details of French nuclear tests at Mururoa Atoll* (21° S, 138° W) *during 1966–68 and approximate dates of arrival of debris at Bombay* (19° N, 73° E), *Pretoria* (26° S, 28° E) *and Aspendale* (38° S, 145° E) *as estimated from short-lived radionuclides in surface air at the stations*

Adapted from Cambray et al., 1966, 1967, 1968 and Rangarajan et al., 1969.

		Bombay		Pretoria		Aspendale	
Test dates	Test yield	Date of first arrival	Travel time (days)	Date of first arrival	Travel time (days)	Date of first arrival	Travel time (days)
1966							
2 July	25 kilotons	3 August	16–32	11–14 July	9–12	19 July	17
19 July	75 kilotons			28 July	9		
11 Sept.	120 kilotons	5 November	31–55	24 Sept.	13	29 Sept.	18
24 Sept.	150 kilotons			7 Oct.	13		
4 Oct.	300 kilotons			19 Oct.	14		
1967							
6 June	Low	23 July	21–47	12–19 June	6–13	19–26 June	13–20
27 June	Low			17–24 July	15–27	17–24 July	15–27
2 July	Low						
1968							
8 July	Medium	25 July	17	15–22 July	7–14	15–22	7–14
15 July	Medium						
3 Aug.	Medium (exptl. device)						
24 Aug.	H-Bomb (2 MT)						
8 Sept.	H-Bomb (2 MT)						

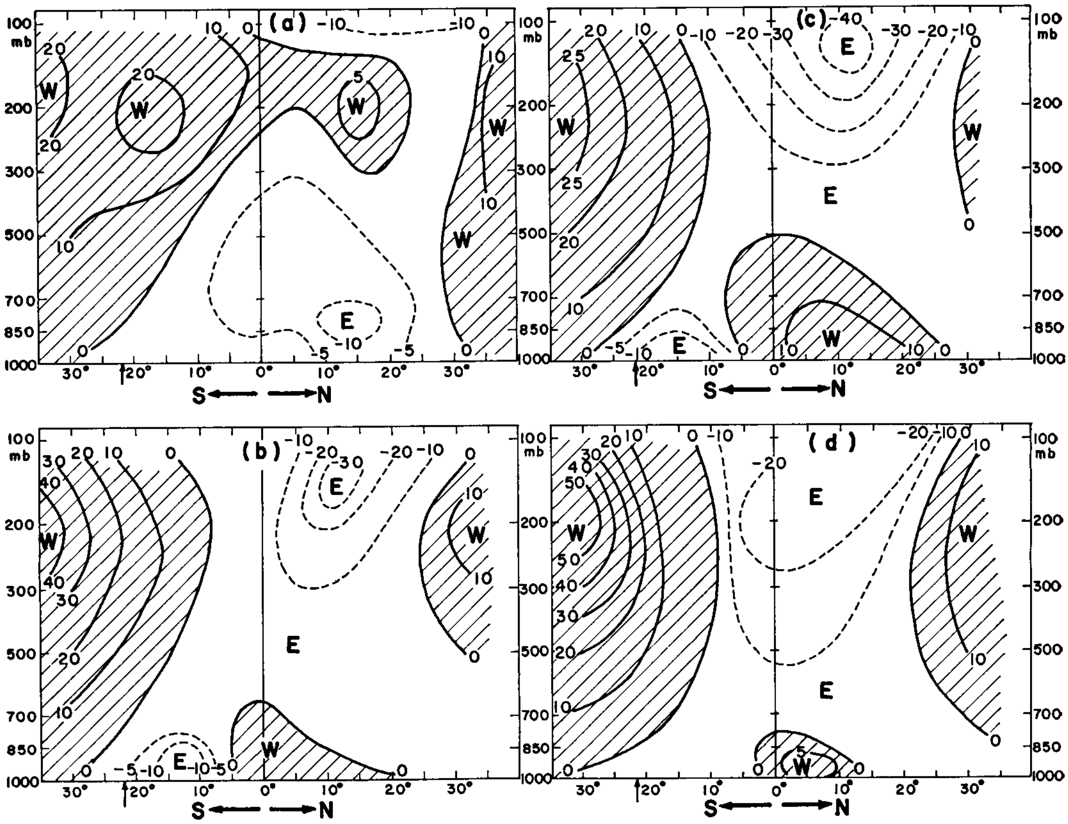

Fig. 6. Vertical distribution of mean zonal components of winds, surface to 100 mb level, between 30° N and 30° S, along four meridian belts during July 1968: (*a*) 60°–80° W; (*b*) 15°–30° E; (*c*) 75°–90° E, and (*d*) 140° E. Shaded area = westerlies. Speed in m/sec, negative for easterlies. The test site latitude is shown by a vertical arrow head on baseline.

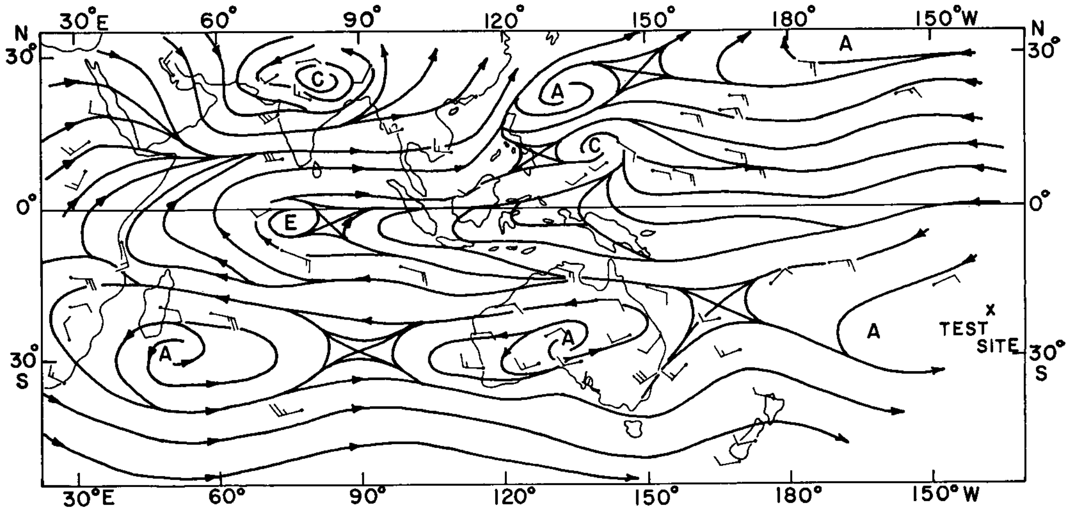

Fig. 7. Mean resultant streamlines at 850 mb level, July, 1968. *C*, cyclonic; *A*, anticyclonic; *E*, equatorial eddy. Position of test site is shown by a cross near bottom right corner.

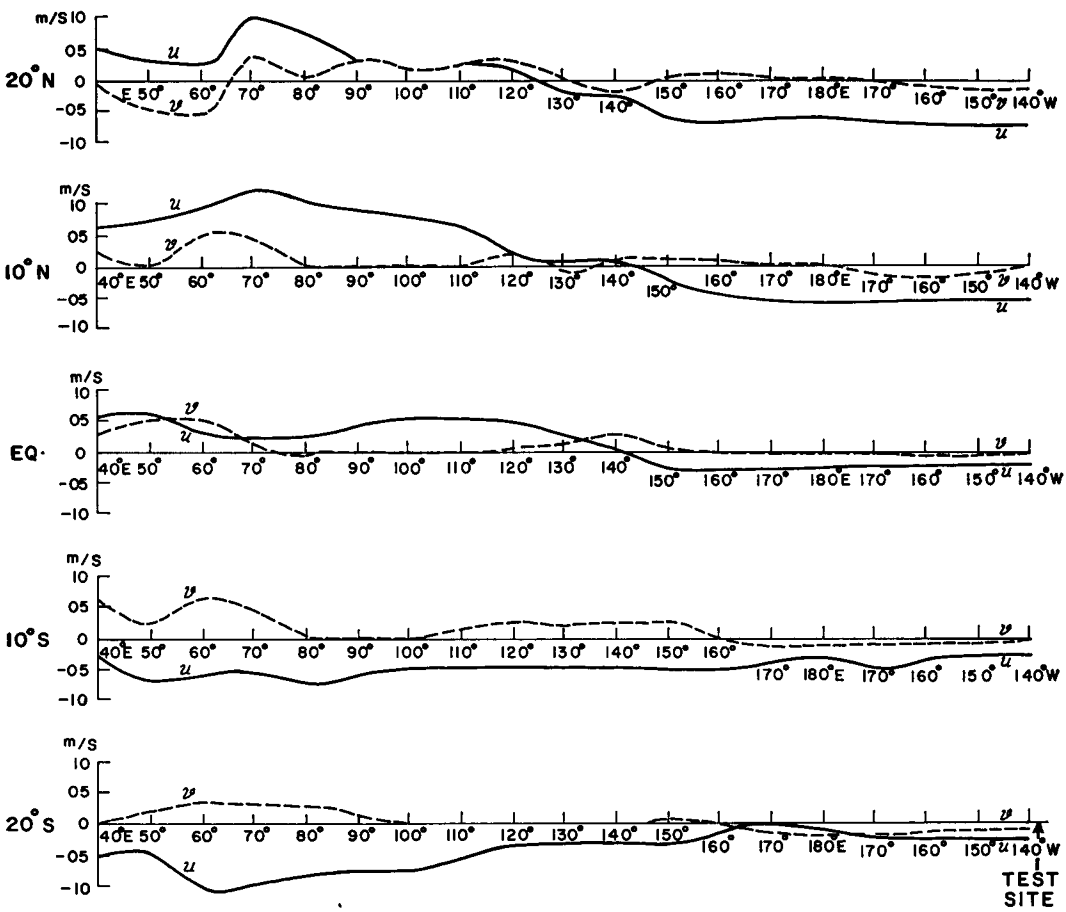

Fig. 8. Distribution of mean zonal and meridional components of winds at 850 mb level, 40° E to 140° W, along the equator and four other latitudes10° and 20°, N and S for situation presented in Fig. 7. Position of test site is shown by arrow head at bottom right corner. u-positive to east; v-positive to north, speed in m/sec.

show that the speed of the westerlies at 300 mb level varies latitudinally with a value of about 20–30 m/sec over the test altitude and higher values to the south up to about 35° S. The strong westerlies move the debris cloud rapidly towards the east. However, it is well known that the tropical westerlies are baroclinically unstable and the large-amplitude wave motion that develops in them produces large scale lateral diffusion. Staley (1963) who studied the lateral diffusion of debris from the 1961 Soviet tests estimated that the lateral diffusion coefficient of the northern hemispheric middle-latitude westerlies was of the order of 10^6 m^2 sec^{-1} or even higher. It is reasonable to expect that similar values may be found for the westerlies of the southern hemisphere. A qualitative evidence of this may be found in Fig. 4 which shows wide meridional dispersion of the debris in the course of the hemispheric flow. One may follow Staley (1963) to compute the lateral diffusion coefficient from Fig. 4 by using the approximate diffusion relation, $y^2(t) = 2\,kt$, where y is the latitudinal gain in time (t) and k is the diffusion constant. A somewhat rough estimate may, however, be obtained from the approximate times of travel of the debris to Aspendale which lies about 17 degrees south of the test latitude. Table 1 shows that the average travel time for the first arrival of the debris in the 3 years 1966/1968 was about 14 days. This would give a minimum lateral diffusion coefficient of 2.8×10^6 m^2 sec^{-1} approximately for the westerlies.

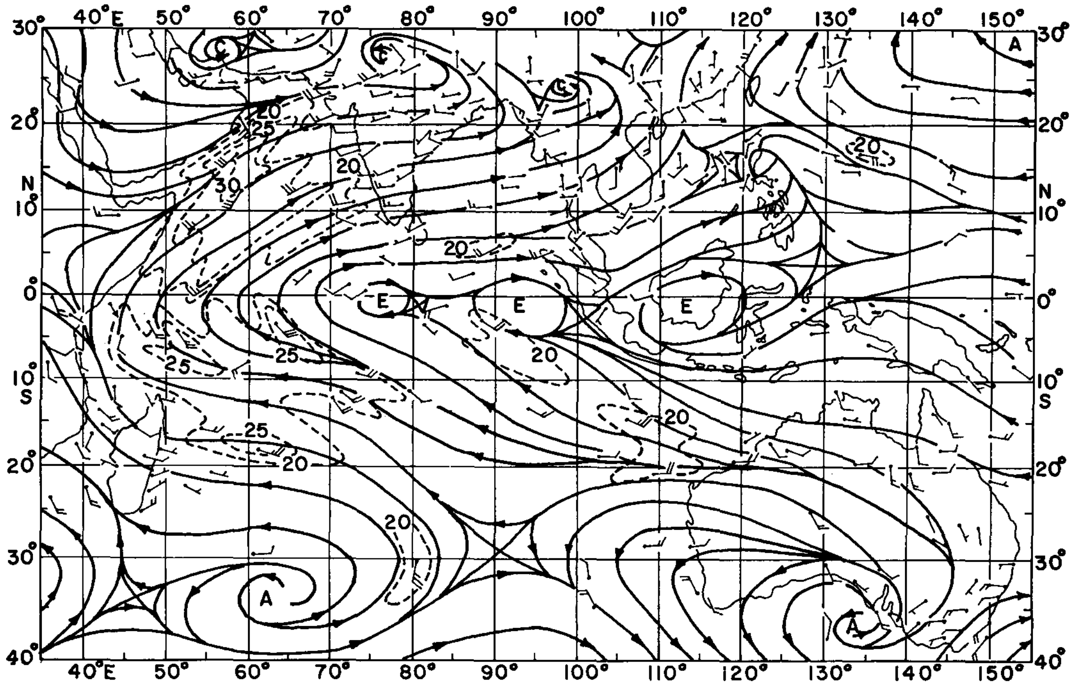

Fig. 9. Surface streamlines and isotachs over IndianOcean and adjoining areas, 12.00 GMT, 12 July 1968. *C*, cyclonic; *A*, anticyclonic; *E*, equatorial eddy.

5. Interhemispheric transport

If the debris cloud is carried from the test site by the hemispheric westerlies, what, then, is the mechanism for interhemispheric transport? It is suggested that transport across the equator in the lower troposphere is effected by the trade-wind circulation in such regions where it has a large meridional component into the opposite hemisphere when by lateral diffusion the tropical westerlies bring the debris to a latitude somewhat close to the equator. It is to be expected that during the course of diffusion, part of the debris cloud would descend to the level of the trade-wind circulation and be transported by this air current. But what are those regions round the globe which have large transequatorial fluxes of air in the lower troposphere? An answer to this question, perhaps, involves consideration of the position of the intertropical convergence zone (ITCZ) in relation to the equator. Fig. 10 shows the mean surface positions of the ITCZ during the two mean monsoon months, February and August. It may be seen that, during August, the ITCZ is located north of the equator practically in all the areas, with maximum displacement in the Afro-Asian monsoon region. During February, the ITCZ is located south of the equator in the Indian Ocean and the western Pacific Ocean but elsewhere it continues to lie north of the equator. Now, if the ITCZ signifies a zone in which air masses from both the hemispheres converge in the lower troposphere, rise, and then diverge in the upper troposphere and stratosphere, then it would seem that its position relative to the equator at any time is important not only for transequatorial flux of radioactive debris, but also for the extent to which the debris can penetrate into the hemisphere. In this sense, the Afro-Asian monsoon region would facilitate maximum interhemispheric penetration. However, if the debris lies in the upper troposphere or stratosphere, the diverging meridional motion may bring it either towards or away from the equator. If it is caught in the poleward drift, it may be carried to the westerly belt where it can dif-

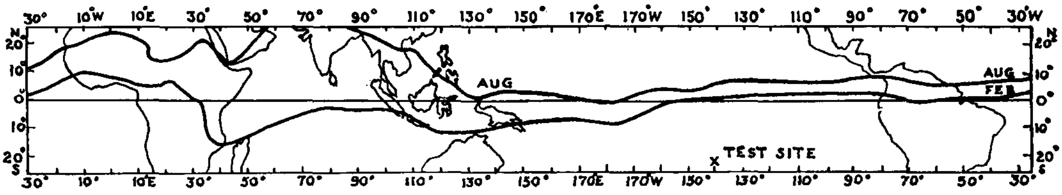

Fig. 10. Mean surface positions of the intertropical convergence zone during February and August.

fuse to higher latitudes. Staley (1963) is of the view that the rapid escape of the debris of the April 1962 high-yield American test on Christmas Island to the southern hemisphere occurred through the southward meridional motion in the upper troposphere and stratosphere. Observational data showing the meridional wind components at standard pressure levels upto 100 mb level along a few selected meridians in the Indian Ocean region at a single maptime in July 1963 have been presented by Saha (1968).

Transequatorial flux of the 1966–68 French test debris through monsoon circulation has been suggested by a number of workers (e.g. Cambray et al., 1968; Rangarajan et al., 1969*a*).

6. Quantitative estimates of transequatorial flux

Pisharoty (1965) who studied water vapour budget over the Arabian Sea computed the net northward flux of water vapour across an equatorial vertical section extending from 42° E to 75° E and from surface to 450 mb level and found the value to be 2.20×10^{10} tons/day during July, 1964. He considered this value to be quite small compared with the value of net eastward flux across a similar vertical section along the west coast of India and concluded that the Indian SW monsoon was primarily a northern hemispheric trade wind system with little drawal of water vapour from the southern hemisphere. In a recent article (Saha, 1970) the author has carried out a fresh computation of equatorial fluxes of air and water vapour using Pisharoty's equatorial section but more representative data and shown that the net northward fluxes of air and water vapour across the equator during July, 1964 were 5.02×10^{12} tons/day and 4.43×10^{10} tons/day respectively. Findlater (1969) using an equatorial vertical section extending from 35° E to 75° E and from surface to 600 mb level and strong low level meridional winds across east Africa reported by him has computed the net fluxes of air across the equator during both summer and winter. His value of the net northward flux of the air during July is 7.68×10^{12} tons/day.

7. Conclusion

The radioactivity and meteorological data discussed in the paper appear to suggest that meridional circulation constitutes the main mechanism to effect interhemispheric transport of radioactive debris in low latitudes. However, the role of the hemispheric westerlies in diffusing the debris cloud laterally to latitudes whence the meridional circulation can effectively move the debris is emphasized. Some quantitative estimates are given of the magnitudes of transequatorial fluxes of air in the western Indian Ocean during northern summer. Transport to higher latitudes in both the hemispheres is possibly effected by westerlies that lie poleward of the meridional circulation cell.

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REFERENCES

Cambray, R. S., Fisher, E. M. R., Brooks, W. L. & Peirson, D. H. 1966. Radioactive fallout in air and rain. Results to the middle of 1966, AERE-R-5260.

— 1967. Radioactive fallout in air and rain. Results to the middle of 1967, AERE-R-5575.

— 1968. Radioactive fallout in air and rain. Results to the middle of 1968, AERE-R-5899.

Findlater, J. 1969. Interhemispheric transport of air in the lower troposphere over the Western Indian Ocean. *Quart. J. R. Met. Soc. 95*, 400–403.

Gustafson, P. F., et al. 1968. Possible evidence of radioactivity from southern hemisphere nuclear tests in surface air over the central United States. USAEC Report, HASL-204.

Junge, C. E. 1962. Note on the exchange rate between the northern and southern atmosphere. *Tellus 14*, 242–246.

Kellogg, W. W., Rapp, R. R. & Greenfield, S. M. 1957. Close-in fallout. *J. Met. 14*, 1–8.

Pisharoty, P. R. 1965. Evaporation from the Arabian sea and the Indian southwest monsoon. *Proc. Sym. Met. Results IIOE*, Bombay, pp. 22–26 (ed. P. R. Pisharoty).

Rangarajan, C. & Gopalakrishnan, S. 1969*a*. Transport and interhemispheric mixing of radioactive debris from recent nuclear tests. Bhabha Atomic Research Center, Report No. 393.

Rangarajan, C., Gopalakrishnan, S. & Vohra, K. G. 1969*b*. Interhemispheric mixing of fallout debris in monsoon regions. CACR symposium at Heidelberg, Sept. 8–13 (paper presented).

Saha, K. R. 1968. On the instantaneous distribution of vertical velocity in the monsoon field and structure of the monsoon circulation. *Tellus 20*, 601–620.

— 1970. Air and water vapour transport across the equator in the west Indian ocean during the northern summer. *Tellus 22* (6).

Staley, D. O. 1963. Atmospheric circulation from fission product radioactivity in surface air. *Science 140*, 667–670.

Volchok, H. L. & Kleinman, M. T. 1969. Radionuclides in surface air. USAEC Report, HASL-207 app. pp. Cl – C 76.

Woodward, R. N. 1966. Transfer of northern hemisphere fallout to the southern hemisphere. *Nature 210*, 5042.

ОБМЕН РАДИОАКТИВНЫМИ ЗАГРЯЗНЕНИЯМИ МЕЖДУ ПОЛУСФЕРАМИ И ЦИРКУЛЯЦИЯ В ТРОПИКАХ

После французских ядерных испытаний на атолле Муруроа в южной части Тихого океана (21° ю. ш., 138° з. д.) в периоды лета в северном полушарии в 1966–68 гг. были измерены высокие уровни радиоактивности приземного воздуха на станциях в обоих полушариях. В частности, эффекты испытаний 1968 г. были обнаружены в северном полушарии вплоть до широты порядка 50° с. ш. Представляются данные для ряда станций. С целью определения воздушных потоков, переносивших радиоактивные загрязнения в северное полушарие в 1968 г., проанализированы доступные метеорологические данные за этот год. Данные по южной части Тихого океана, по-видимому, исключают возможность, что загрязнения с места испытаний переносились к экватору и за него посредством лишь пассатной циркуляции нижней тропосферы. На основе представленных данных о глобальной тропосферной циркуляции предположено, что перенос из одного полушария в другое был подвержен влиянию пассатной циркуляции после того, как загрязнения были перенесены тропическими экваториальными ветрами до экваториальных широт путем поперечной горизонтальной диффузии. Имеющиеся данные позволяют оценить, что коэффициент поперечной диффузии для тропических западных ветров южного полушария порядка 10^6 $м^2$ $сек^{-1}$ или более. В западной части Индийского океана пассаты вблизи экватора имеют большую меридиональную компоненту, поэтому, когда загрязнения поступают сюда с помощью тропических западных ветров, они быстро переносятся через экватор пассатной циркуляцией. Представляется, что данная работа качественно подтверждает более раннее исследование в отношении потоков воздуха через экватор в нижней тропосфере в западной части Индийского океана в период летних муссонов и позволяет сделать общий вывод, что большие потоки воздуха через экватор должны происходить в тех областях, где зона междутропической конвергенции находится в достаточном удалении от экватора в противоположном полушарии. Меридиональные движения, связанные с этой зоной конвергенции, переносят загрязнения в направлении к экватору или к полюсу в зависимости от ее положения внутри полушария. В случае переноса к полюсу загрязнения могут достичь широты, от которой западные ветры могут их рассеять до более высоких широт.